Identification of infrasound produced by sprites during the Sprite2003 campaign

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[1] During the summer of 2003, complementary measurements were taken in Europe during the Sprite2003 campaign to study sprites and associated processes. On July 21, 28 sprites observed by light-sensitive optical cameras located at the Observatoire du Pic du Midi in the Pyrenees mountains were found to correlate with chirp-like signals of several tenth to few minutes duration, measured by an infrasound station at Flers about 400 km from the thunderstorm. The sprite activity identified by the infrasound signature continued past sunrise into the daytime when optical systems cannot be used, documenting the occurrence of daytime sprites. Using an acoustic wave propagation model, the observed propagation delays, frequency dispersion, and duration of the infrasound bursts are found to be consistent with source altitudes at 60–80 km with horizontal dimensions equal to the optical width of the sprites. The chirp-like dispersion is a result of the propagation properties in the earth-thermosphere waveguide. **Citation:** Farges, T., E. Blanc, A. Le Pichon, T. Neubert, and T. H. Allin (2005), Identification of infrasound produced by sprites during the Sprite2003 campaign, *Geophys. Res. Lett.*, *32*, L01813, doi:10.1029/2004GL021212.

1. Introduction

[2] Sprites are transient luminous events (TLEs) lasting from a few milliseconds up to a few hundred milliseconds. They are generated over thunderstorms at altitudes from ∼40 to ∼85 km by the electric field pulse associated with a positive cloud-to-ground (+CG) lightning flash. Since the first scientific report [*Franz et al.*, 1990], sprites and other forms of TLEs above thunderstorms have been the subject of intense investigation [e.g., *Neubert*, 2003; *Lyons et al.*, 2003a]. Sprites were observed for the first time over Europe in 2000 [*Neubert et al.*, 2001] and have by now been observed in almost every region of the world experiencing intense thunderstorms.

[3] Two different mechanisms for generation of infrasound by lightning have been proposed: 1) the expansion of the rapidly heated lightning channel, and 2) the drag due to the motions of the charged particles [*Uman*, 1987]. Since both of these processes are present in sprites, it is of interest to determine the characteristics of infrasound from sprites. Furthermore, measurements suggesting that sprites can generate infrasound pressure waves have recently been reported, but without distinct signature [*Bedard et al.*, 1999] or without direct sprite-infrasound relation [*Liszka*, 2005].

[4] The main goal of the present paper is to report on the first unambiguous identification of infrasound signals generated by sprites from the simultaneous observation of sprites and infrasound. It will further be shown that identification of the signature allows detection into the daylight. Finally, the prospect of using infrasound for estimates on sprite energy deposition in the atmosphere is discussed.

2. Description of the Experiment

[5] The measurements were taken during the Sprite2003 campaign, which co-coordinated optical observations of sprites from the Observatoire du Pic du Midi in the Pyrenees mountains (Figure 1), infrasound observations from Flers, France, observations of cloud-to-ground (CG) lightning activity from a network of lightning sensors, and electromagnetic wave observations covering frequencies from 1 Hz to several MHz.

[6] The infrasound station is composed of four microbarometers MB2000, which measure the local relative pressure with a sensitivity of 10^{-3} Pa, a band pass of 0.01–27 Hz, and a sampling frequency of 20 Hz [*Le Pichon et al.*, 2002]. These measurements were performed to test instruments and methods and to identify natural infrasound sources in the frame of the Comprehensive Test Ban Treaty verification [*Vivas Veloso et al.*, 2002]. The optical video camera system was automated for sprite detection and remotely operated via the Internet [*Allin et al.*, 2005]. The system consisted of two light-sensitive CCD cameras with a field-of-view of 20° and a video field exposure time of 20 ms. Optical identification of sprites from the system is only possible during the nighttime. The CG lightning characteristics were provided by the Météorage network, with accuracies better than 1 km on location, 10 μs on time, and better than 90% detection efficiency on CG lightning.

[7] Information from the camera system of sprite occurrence times and azimuths relative to the camera location at the Observatoire du Pic du Midi is used to identify the causative positive cloud-to-ground lightning flash (+CG). Sprites are generally within ∼50 km of a +CG with a time delay of a few tens of msec [*São Sabbas et al.*, 2003], and thus the +CG location is used as the approximate geographic location of the sprite source.

[8] More than 130 sprites were observed during the campaign, mainly during eight thunderstorms. For the present analysis the July 21 thunderstorm has been selected because of its proximity of the Flers station (350–500 km). During the storm, 28 sprites were observed by the optical cameras from 0200 UT to 0315 UT, when the cameras were

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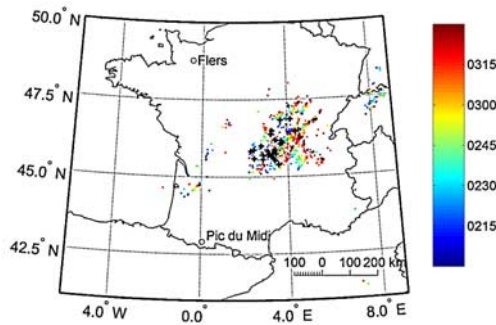[3]Danish Technical University, Lyngby, Denmark.

Figure 1. Map showing the location of the Flers station and Pic du Midi observatory, and of the lightning flashes occurring on July 21st between 0200 and 0330 UT (colored scale). The black crosses indicate the location of the lightning parents of the 28 observed sprites.

shut down because of the approaching dawn (∼1 hour before sunrise).

[9] Generally, when a thunderstorm is closer than 50 km from Flers, infrasound bursts are observed from lightning flashes. These bursts are characterized by a mean duration from 5 to 20 seconds and a spectral content from 0.1 to 10 Hz, with the spectral energy density decreasing with frequency. Their amplitudes are up to 5 Pa and decrease with distance to the source. These main characteristics are in good agreement with previous observations of infrasound produced by lightning [*Uman*, 1987]. During the July 21 thunderstorm, these lightning related infrasound were not observed at the Flers station.

3. Observations

[10] Using propagation model estimates of propagation time from the source to the infrasound detector, described in the next section, the infrasound data has been searched for signatures of sprite events. Figure 2a shows a sprite taken at 0217:00.880 UT, the relative pressure signal measured from 0240 and 0243 UT and the corresponding spectrograms in the spectral bands 0.1–1 Hz and 1–9 Hz. This event is the largest (0.2 Pa) and the longest (∼150s) of the storm. The 1–9 Hz spectrogram shows a chirp-like feature with the low frequencies arriving before the high frequencies, as already observed by *Liszka* [2005]. A dispersive signal is also present in the 0.1–1 Hz band; however, the signal is noisier than in the 1–9 Hz band.

[11] Figure 2b shows an example of three sprites during a 3-minutes interval and of the corresponding 1–9 Hz infrasound signals. The dispersion is comparable, although more complex with the signals decreasing in frequency before rising.

[12] Most of the parent lightning of the 28 sprites observed during this storm were located between 370 and 450 km from the Flers station. 70% of these 28 sprites have been linked with a chirp infrasound using the computed propagation time of infrasound from the source to the sensor assuming a source at 60 km. The 30% other sprites, for which infrasound were not observed, were weaker and smaller. All the observed chirp infrasound signals were related with sprites one to one during the camera observation period.

[13] Around dawn, after the camera was shut down, between 0315 and 0600 UT, 8 additional chirp infrasound signals were observed. The most intense chirp infrasound event between 0230 and 0600 UT was measured just before the sunrise (Table 1). After 06 UT, the storm was weaker and at larger distance.

4. Infrasound Propagation Modeling

[14] The propagation time to Flers is estimated by a paraxial ray-tracing model [*Virieux et al.*, 2004]. The atmospheric part is described by sound velocity and wind speed profiles obtained from the time-varying MSISE-90 and HWM-93 empirical reference models [*Hedin et al.*, 1991]. Rays were injected at altitudes of 0, 60 and 80 km with elevation angles between 0 and 180 (Figure 3a). As seen on the figure, infrasound propagates in the ground-thermosphere waveguide. The time of arrival of infrasound at the sensor is determined for the three source altitudes with steps of 0.5° (Figure 3b). The principal error in the calculation of the time delay is related to the estimate of the sprite location. The sprite may be up to 80 km from the parent lightning with a mean distance of 50 km as observed in US thunderstorms [*São Sabbas et al.*, 2003]. The maximum error in the arrival time is then of the order of ±2 minutes.

5. Discussion

[15] All the infrasound chirp signals, observed during nighttime, were related with sprites, the lightning parents
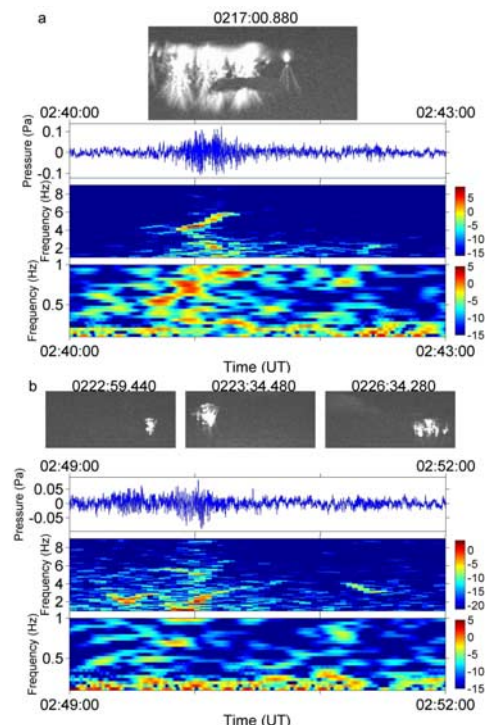

Figure 2. Images of sprites and associated infrasound signals. The infrasound spectrograms are given for two ranges 1–9 Hz and 0.1–1 Hz. The color scales are in dB. Sprites are observed at: a) 0217:00.880 UT, b) 0222:59.440, 0223:34.480 and 0226:34.280 UT.

Table 1. Statistics of the Chirp Infrasound Signals During Nighttime (Two First Lines) and Daytime (Last Line)[a]

Infrasound Time (UT)	Number of Bursts	Amplitude (Pa)			Duration(s)			Mean Propagation Time (min)		
		Min	Max	Avg	Min	Max	Avg	Measured	Calculated	Difference
0230−0350	19	0.07	0.30	0.14	18	149	63	27.0 ± 2.1	27.0 ± 1.0	0.3 ± 1.8
0350−0450	5	0.09	0.58	0.31	29	133	73	not available	not available	not available
0450−0600	3	0.17	0.35	0.26	58	134	100	not available	not available	not available

[a]The second line indicates the number of infrasound measured when the camera was shut down on account of dawn light, but when the sprite initiation conditions were the nighttime ones.

being located between 370 and 450 km from Flers. This observation is well represented by a ray tracing with an infrasound source between 60 and 80 km producing downward rays (in red in Figure 3a) reaching the ground between 370 and 450 km (Figure 3b). The same ray tracing performed for a source located at the ground level shows a quasi-silence area between 370 and 450 km: 18% of the rays reaching the ground from 280 to 500 km reach it between 370 and 450 km when 65% reach it between 280 and 370 km. Results for altitudes from 20 to 50 km, located below the maximum of temperature of the stratosphere, are comparable with rays coming back to the ground before 370 km. As the altitude range between 60 and 80 km provides the best representation of the observations, it is a good candidate for being the sprite infrasound production altitude.

[16] Spider lightning are associated, in certain cases, with large sprites. These lightning are very rare, their horizontal size exceeds 50 km and their charge is in the range of few hundreds of Coulombs, that is ten times more than regular lightning [Lyons et al., 2003b]. For this kind of lightning, infrasound waves can be expected at distance higher than 50 km from the source, but such infrasound were never observed up to now. As the ray tracing shows that Flers is located in a quasi silent zone, relatively to the location of the thunderstorm for low altitude sources, these lightning are not expected to be the source of the detected chirp infrasound. This is confirmed by the direct relation one to one between the 19 chirp infrasound signals and the sprites.
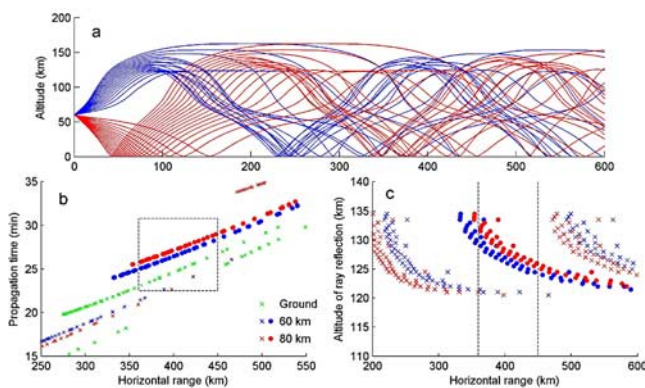

Figure 3. a) Ray tracing for a source at 60 km altitude including realistic temperature and wind model for July 21st at 0200 UT in France. b) Propagation time versus the distance between the sprite and the Flers station for three source altitudes (disk for downward rays and cross for upward rays). The dashed rectangle delimits the time and range corresponding to the sprite observations. c) Altitude of reflection for each ray in function of the distance sprite/Flers.

The spider lightning can be related with large sprites but sprites are not always related with spider lightning.

[17] At a sound velocity of about 300 m/s, horizontal sizes of sprites between 10 and 50 km correspond to propagation times between 30 and 160 s, which are values comparable with the observed infrasound burst durations (Figure 4). As the lines of sight from the two sites (Flers and Pic du Midi) are almost orthogonal, the horizontal extension measured on the sprite image can be directly related to the signal duration observed from Flers. The linear correlation coefficient is good (∼80%), and the dashed line, which has a slope equal to a velocity of 300 m/s, describes rather well the relation between both values. This shows that the duration of the infrasound burst represents the horizontal size of the sprite rather than the duration of the source.

[18] The dispersion in frequency, with the low frequencies arriving before the high frequencies, may be due to the different propagation paths followed from the source. The thermosphere acts as a low-pass filter, where a wave is damped as it reflects at the upper waveguide boundary [Blanc, 1985]. The cutoff frequency decreases when the altitude increases. Figure 3c shows the altitude of reflection of each ray. The rays coming from a source distant of 380 km from the sensor are reflected at 135−150 km with a cutoff frequency of ∼1 Hz, while rays coming from a source located 50 km beyond, are reflected at ∼120 km with a higher cutoff frequency of ∼5 Hz. If the sprite infrasound spectral maximum is higher than 5 Hz, the chirp-shape can be explained by the horizontal size of the sprite because the wave coming from the nearest side of the sprite (relatively to the sensor) reflects at higher altitude than the wave generated from the farthest side. For smaller sprites, the dispersion effect is weaker because the rays are reflected about in the same range of altitude.

[19] Height sprites were observed up to 06 UT while the cameras were shut down: 5 detected in nighttime condition but before sunrise, and 3 measured during the first hour following the sunrise (Table 1). This shows the possibility to use infrasound for the monitoring of sprites during daytime. The number of such infrasound is weaker than during nighttime, probably due to the growing difficulty to initiate sprite taking into account to the increase of the conductivity
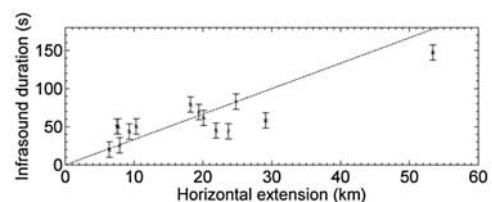

Figure 4. Infrasound duration versus horizontal sprite extension.

in the lower ionosphere during daytime [*Stanley et al.*, 2000]. The initiation of sprite during daytime needs lightning with large charge moment. However, Stanley et al. considered conditions ~2 hours before sunset when the electron density is 10–20 times higher than during the first hour after sunrise.

[20] Infrasound detection will allow estimate of energy deposition of sprites into the atmosphere with a method independent of an optical one which gives values of 1–10 MJ [*Sentman et al.*, 2003] up to ~1 GJ [*Heavner et al.*, 2000] for large events. According to *Whitaker et al.* [2003] pressure-distance-yield relation, deduced from high explosive test at ground-level, the sprite measured overpressures would correspond to an explosion of 10–100 tons of TNT equivalent yield. Considering an increase of the efficiency of an explosive source located at altitudes of ~60 km to produce pressure waves the July 21 sprite equivalent yield would be comprised between 0.1–10 tons of TNT (that is 0.4–40 GJ).

[21] To conclude, this paper presents the first unambiguous observation of infrasound related with sprites. The infrasound measurements, with a potential greater range of observation possibility than optical system, could be an important method to monitor the sprite activity thanks to global infrasound networks.

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